Multiaxial rate dependent behaviour of Ti6Al4V

Govind GourA[1a], Yuan Xu[2], and Antonio Pellegrino[3]

[1]Department of Engineering Science, University of Oxford, Oxfordshire, Parks Road, OX1 3PJ, United Kingdom.

[2]School of Engineering, Newcastle University.

[3]Department of Mechanical Engineering, Centre for integrated Materials, Process & Structures (IMPS), University of Bath.

[a]*govind.gour@eng.ox.ac.uk.*

Abstract. The mechanical response of the titanium alloys under combined tension-torsion loading conditions at low rate and high strain rate was studied. A detailed campaign carried out on the conventional industry standard, Ti6Al4V. A comprehensive investigation into the mechanical performance and failure mechanism of these two alloys was conducted across a wide range of stress states, encompassing uniaxial tension, pure torsion, shear-dominant combined tension-shear, and tension-dominant combined tension-shear. Low rate (10^{-3} s^{-1}) testing carried out using multiple cameras setup with universal screw driven machine. An innovative tension-torsion split Hopkinson bar (TTHB) setup, equipped with multiple high-speed cameras, was employed to investigate the behaviour of the titanium alloys under combined loading conditions at high strain rates (10^3 s^{-1}). The dynamic multiaxial experiments showcased the TTHB setup's capability to synchronize the longitudinal and torsional waves upon loading the specimen, maintain dynamic equilibrium, and constant strain rate loading. A distinct geometry of the specimen containing four flat dog bones arranged circumferentially at the gauge section was used. A multiaxial failure locus for Ti6Al4V was established in the normal versus shear stress space, incorporating experimental outcome spanning from quasi-static to high strain rate. Utilising experimental measurements, failure envelopes were constructed, and an analysis of loading paths revealed strain history proportionality in combined tension-torsion experiments. This study reports, for the first time, the failure stress locus of Ti6Al4V along with their rate-dependent characteristics.

Introduction

Titanium and its alloys are increasingly attracting attention across diverse sectors such as military, biomedical, aerospace, and civilian transportation, thanks to their distinct advantages, notably their remarkable strength-to-weight ratio. Within the aerospace industry, titanium alloys are favored primarily for their ability to reduce weight and act as substitutes for steel, while maintaining functionality across a broad temperature spectrum. However, occurrences such as foreign particle ingestion, fan blade detachment, or blade tip interactions with fan casings result in combined stress conditions on the fan casings. The nature and intensity of these stresses vary depending on the type of impact. Depending on the impact's characteristics, the resulting stresses may encompass a combination of normal and shear forces. For example, aircraft frames, jet engine fan enclosures, joint replacement systems, high-pressure compressors, and specific components in landing gear frequently experience combined loading scenarios due to the complex nature of their operational environments [1-4]. Sato et. al [5] assessed adhesively bonded joints using split Hopkinson bar with clamping equipment to combined loads of tension and torsion. Chen et al [6] conducted an experimental study on pure titanium under various combination of tension-torsion loading at low rate. The outcome focused on the microstructure and fracture morphology of the tested specimens, but no stress-strain relation was reported. In a recent advancement, Xu et al. [7] developed a novel testing apparatus and methods to characterize the multiaxial deformation and failure of engineering materials under high strain rates . They utilized an innovative Tension-Torsion split Hokinson Bar (TTHB) incorporating an energy storage and release mechanism. This setup facilitated the generation of both longitudinal and shear waves through the swift release of jaw-shaped clamps. With this experimental apparatus a series of combined high-rate tension-torsion experiments have been conducted on commercially pure titanium at strain rates ranging from 10^{-3} s^{-1} to 10^3 s^{-1}. This investigation utilized tubular shape specimens. The multiaxial failure stress locus was constructed in the normal versus shear stress space at low and high strain rates. With these measurements, the Drucker-Prager criterion was employed to approximate the failure loci and evaluate the rate sensitivity of the material. The analysis reveals a moderate level of tension-compression asymmetry, both at quasi-static and dynamic strain rates. The aim was to inspire the development novel and accurate constitutive models for engineering materials. In this research, a distinctive specimen configuration involving four flat dog-bones arranged in a circular fashion is selected. Each dog-bone features dimensions with a gauge length of 1 mm, a width of 1.5 mm, and a thickness of 0.75 mm, as shown in Figure 1 (b). High strain rate combined loading experiments were conducted utilizing an internally developed Tension-Torsion Split Hopkinson Bar apparatus (TTHB) [8], see Figure 1 (a), facilitating the direct measurement of the high-rate failure and yield surfaces from experimental data. Two high-speed cameras, Photron SA-5, were synchronized and directed towards two ligaments to capture macroscopic deformation mechanisms and to document failure initiation on the specimen surfaces. A fine grey-scale speckle pattern was applied to the specimen surface to enable full-field tensile and shear strain measurements through digital image correlation (DIC) analysis of high-resolution video footage. The acquired images were processed using the commercial software GOM ARAMIS®. An sequence of combined tension-torsion high frame rate images is presented in Figure 1 (c). Additionally, the data acquisition system incorporated longitudinal and shear strain gauges on both the input and output bars to capture tensile and torsional wave histories. Figure 1 (d) presents the summary of the measured experimental results to better understand the failure of Ti6Al4V under combined loading and delineate the failure locus as a function of ultimate tensile and shear stress at quasi-static and high strain rate. The Drucker-Prager (D-P) criterion is employed to approximate the experimental failure envelopes.

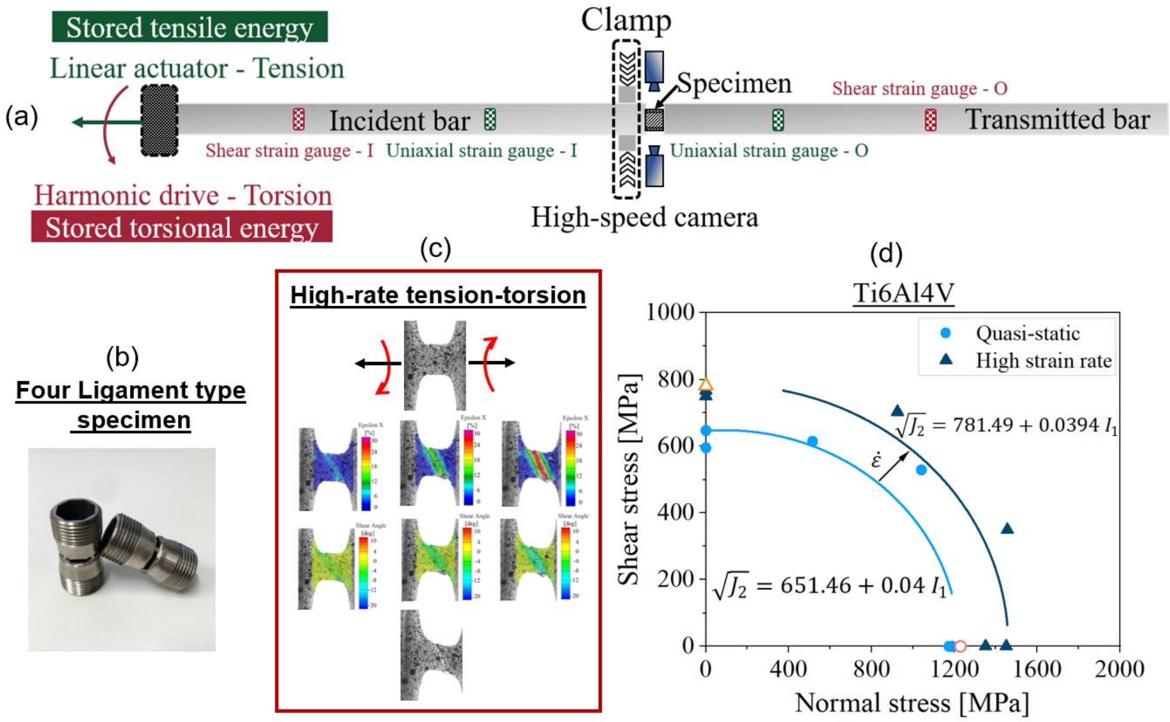

Figure 1:(a) A schematic of In-house developed Tension-Torsion Hopkinson bar [9-11], (b) real four ligament type specimen [12, 13], (c) Progressive deformation and failure under high-rate combined loading of Ti6Al4V (d) Failure locus of Yield locus of Ti6Al4V at quasi-static and high strain rate.

References

1. Boyer, R.R., *An overview on the use of titanium in the aerospace industry.* Materials Science and Engineering: A, 1996. **213**(1-2): p. 103-114.
2. Shalaby, H., et al., *Failure of titanium condenser tube.* Engineering Failure Analysis, 2011. **18**(8): p. 1990-1997.
3. Chen, Q. and G.A. Thouas, *Metallic implant biomaterials.* Materials Science and Engineering: R: Reports, 2015. **87**: p. 1-57.
4. Ma, T.-H., et al., *Comparison of multiaxial low cycle fatigue behavior of CP-Ti under strain-controlled mode at different multiaxial strain ratios.* International Journal of Fatigue, 2020. **140**: p. 105818.
5. Sato, C. and K. Ikegami, *Strength of adhesively-bonded butt joints of tubes subjected to combined high-rate loads.* The Journal of Adhesion, 1999. **70**(1-2): p. 57-73.
6. Chen, H., et al., *Experimental study on pure titanium subjected to different combined tension and torsion deformation processes.* Materials Science and Engineering: A, 2017. **680**: p. 278-290.
7. Xu, Y., et al., *Optimal Design, Development and Experimental Analysis of a Tension–Torsion Hopkinson Bar for the Understanding of Complex Impact Loading Scenarios.* Experimental Mechanics, 2023. **63**(4): p. 773-789.
8. Xu, Y., et al., *Experimental analysis of the multiaxial failure stress locus of commercially pure titanium at low and high rates of strain.* International Journal of Impact Engineering, 2022. **170**: p. 104341.
9. Zhou, J., et al., *Piezo-driven clamp release for synchronisation and timing of combined direct-shear stress waves.* International Journal of Impact Engineering, 2023. **180**: p. 104672.
10. Xu, Y., et al., *Effects of build orientation and strain rate on the tensile-shear behaviour of polyamide-12 manufactured via laser powder bed fusion.* Materials & Design, 2023. **232**: p. 112162.
11. Zhou, J., et al., *The mechanical response of commercially pure copper under multiaxial loading at low and high strain rates.* International Journal of Mechanical Sciences, 2022. **224**: p. 107340.
12. Xu, Y., et al. *A Novel Specimen Design for Multiaxial Loading Experiments at High Strain Rates*. in *Society for Experimental Mechanics Annual Conference and Exposition*. 2023. Springer.
13. Xu, Y. and A. Pellegrino. *A Novel Apparatus and Methodology to Characterise the High-Rate Behaviour of Materials Under Complex Loading Conditions*. in *Italian Workshop on Shell and Spatial Structures*. 2023. Springer.